ESSERC 2024

SiNANO-ICOS-INPACE Workshop

"Emerging technologies in Advanced Computation, Advanced Functionalities, Ground-breaking Technologies: Impact on International Cooperation"

Smart Sensors

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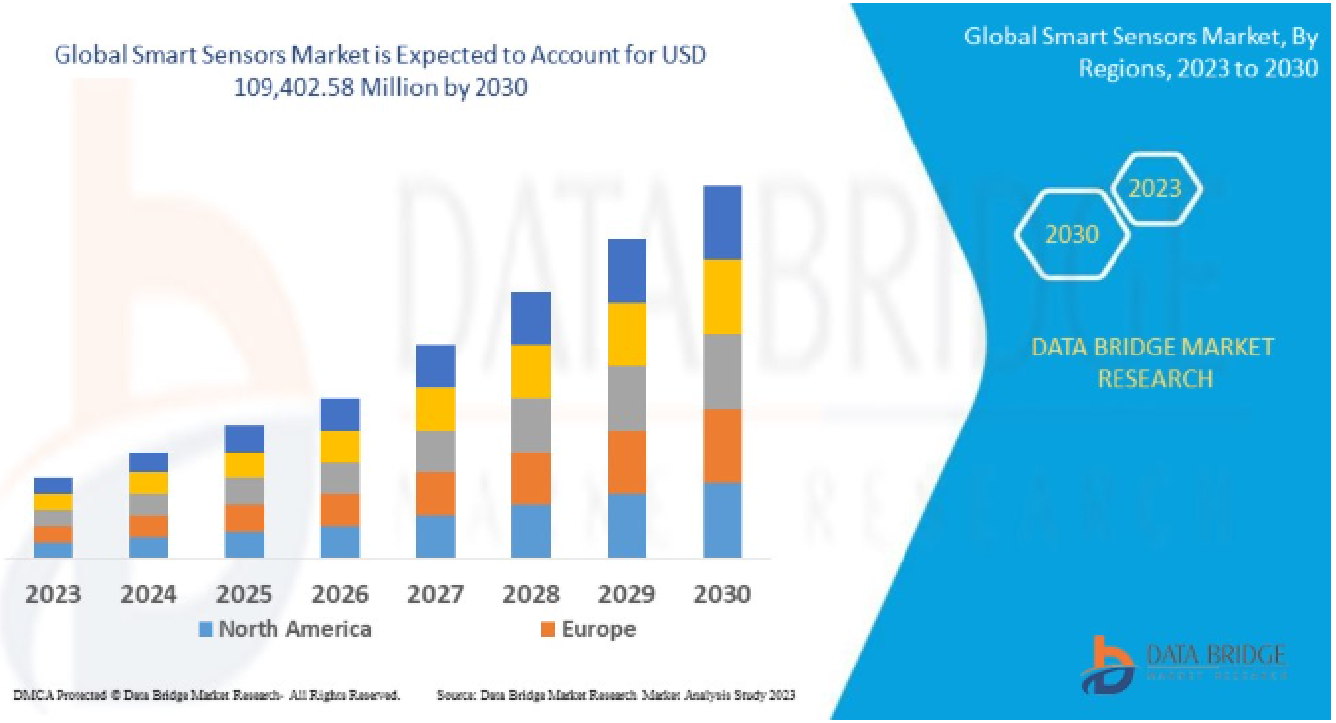
Bruges, September 9, 2024

Introduction

- Global smart sensor technology used in healthcare, automotive, environment, agriculture, smart cities, and energy applications.
- As of 2024, there are approximately 18.8 billion connected IoT devices globally and is expected to reach approximately 32.1 billion by 2030
- Role of edge-of-the cloud devices and the generation of big data are expected to drive the creation of new ecosystems and include 11% of the world economy by 2030
- The compound annual growth rate (CAGR) for the smart sensors market is expected to be around 19.0% between 2024 and 2030.
- North America/Canada having the largest share of the market followed closely by the Europe, Asia and the rest of the world

Technology Market

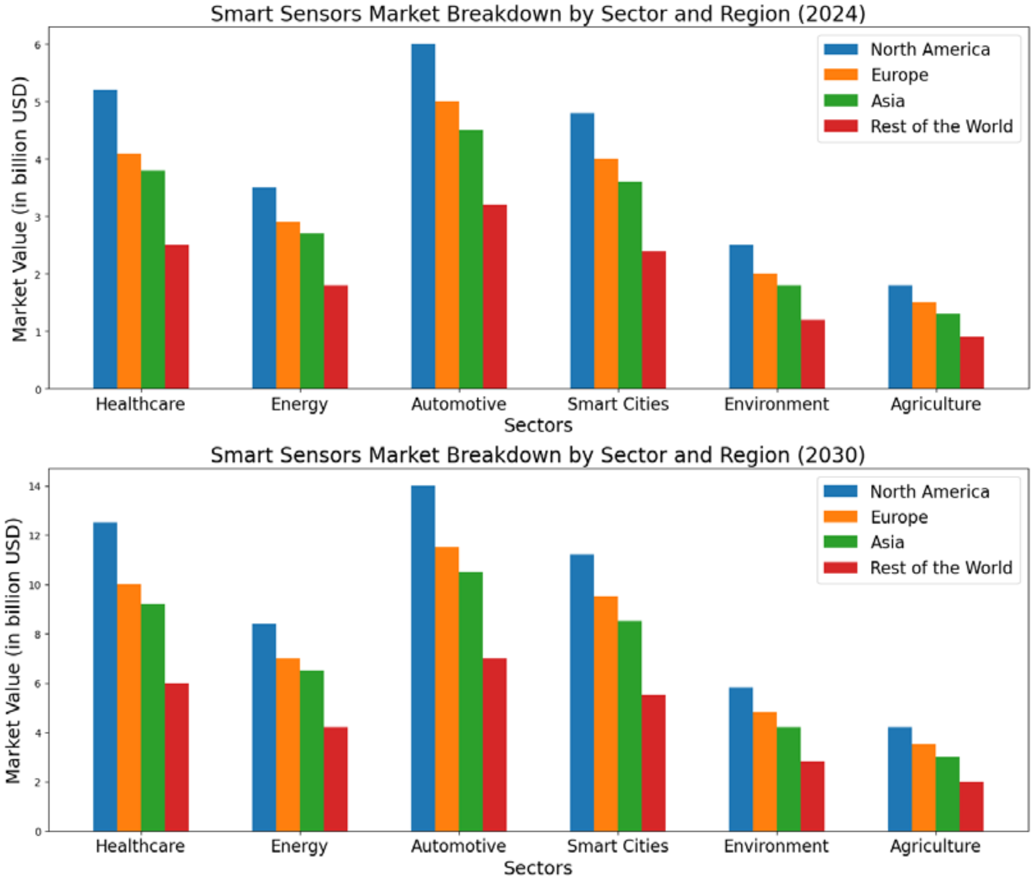


1.MEMS (Micro-Electro-Mechanical Systems): This segment is expected to hold a significant share of the market, driven by its applications in consumer electronics, automotive, and industrial sectors. **USD 35 billion** by 2030

2.CMOS (Complementary Metal-Oxide-Semiconductor): CMOS sensors, primarily used in imaging applications, are anticipated to grow substantially. USD 25 billion by 2030

3.Optical: With the increasing demand for miniaturized and integrated sensor solutions, **USD 20 billion** by 2030

Technology Market by sector



Global values 2024 ➔ 2030

Healthcare: $15.6 ➔ $37.7 billion

Energy: $10.9 ➔ $26.1 billion

Automotive:$18.7 ➔ $43 billion

Smart Cities:$14.8 ➔ $35 billion

Environment: $7.5 ➔ $17.6 billion

Agriculture: $5 ➔ $15 billion

Sources:
grandviewresearch.com
mordorintelligence.com
market.us
emergenresearch.com
theinsightpartners.com

Technology Status & Requirements

Medical - Highly sterile

Automotive - Temperature

On-Farm

A key challenge in the development of smart sensor systems is that a "**one size fits all" approach is not possible** due to the myriad of different deployment scenarios

Consequently, new or existing sensing paradigms must be developed or modified to render them **fit-for-purpose**

Application Concepts 2020

- Concept 1—Motion Sensors
- Concept 2—Pressure Sensors
- Concept 3—Advanced Drive Assistance Systems
- Concept 4—Environmental Sensors
- Concept 5—Agri-food Sensors
- Concept 6—Sensors for Medical and Healthcare Applications
- Concept 7—Molecular Diagnostics
- Concept 8—Native CMOS-based physical sensor interfaces

Sensor Concepts 2024

- Concept 1—Motion Sensors
- Concept 2—Pressure Sensors
- Concept 3—Advanced Drive Assistance Systems
- Concept 4—Environmental Sensors
- Concept 5—Agri-food Sensors
- Concept 6—Sensors for Medical and Healthcare Applications
- Concept 7—Molecular Diagnostics
- Concept 8—Native CMOS-based physical sensor interfaces
- Concept 9—Sensors for energy (new)
- Concept 10—Sensors for Smart Cities (new)

Challenges

Difficult Challenges 2019-2025	*Summary of Issues*
MEMS (highest accuracy, stability, power consumption and miniaturization)	3-axis accelerometers 3-axis gyroscopes IMU/iNEMO SiP inertial modules (accelerometer, gyroscope, magnetometer) Low accuracy
Pressure sensors (automotive and medical applications)	Medical applications (e.g., blood pressure, bladder examination) Pressure monitoring system (barometric air pressure)
Advanced Drive Assistance Systems (image sensors, LiDAR, infrared sensors, and radar sensors)	Improve sensitivity, with smaller pixel size ; flicker-free and HDR n-cabin near-IR global shutter; 3D cameras Improve resolution Long, short/medium range radar; silicon, silicon germanium
Patient-based devices; hospital-based devices	Blood glucose meter, cardio meter; activity monitor-actimetry Blood pressure meters monitor
Implantable sensors	Vision, ear, orthopedic, cardiac, neural/brain Critical to the final sensor performance Difficult, expensive and time consuming validation tests and certifications. A few centimeters implant depth The basic technology of low-temperature silicon nanowires growth on CMOS, to be used in many different electrophysiology meters directly at cellular level.
Molecular diagnostics	Infectious disease, cancer, other disorders medical diagnostics Functionalization of CMOS IC, optimization of image sensors as fluorescence detectors

Challenges

Difficult Challenges 2025-2034	*Summary of Issues*
MEMS (highest accuracy, stability, power consumption and miniaturization)	IMU/iNEMO SiP inertial modules (accelerometer, gyroscope, magnetometer) High reliability and quality, low price, and ultra-low power consumption for portable application and implantable devices
Pressure sensors (automotive and medical applications)	Automotive application (pressure monitoring system—tire pressure monitor, air bag development) Tactile sensors for fall detection Packaging
Advanced Drive Assistance Systems (image sensors, LiDAR, Infrared sensors, and radar sensors)	New sensing layer to replace silicon; local computer vision; global shutter/ flicker-free/ HDR; secured data links; 3D cameras; photodetectors Reduce cost; data fusion with CMOS imaging sensor; microbolometers Higher integration into a small module, laser scanner, Long, short/ medium range radar; silicon, silicon germanium
Environmental sensors	Gas sensors (CO, SO_2, NO_2, O_3) market introduction Particulate matter detection (PM2.5, PM10) market introduction Toxic, explosive, fire, or injurious gases (industrial, infrastructure), market introduction Polymer and carbon based sensing—R&D Quantum dots, nanotubes and nanowires—R&D Moisture absorbing material—humidity monitoring

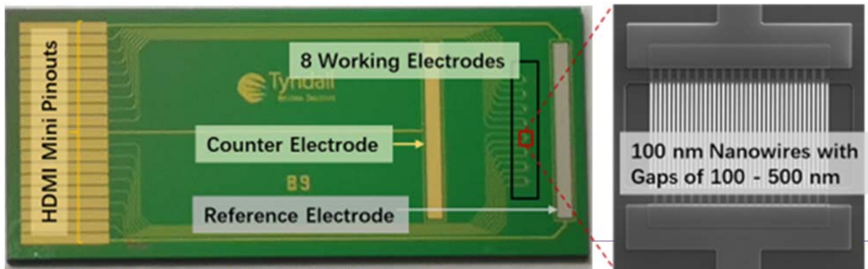
Challenges

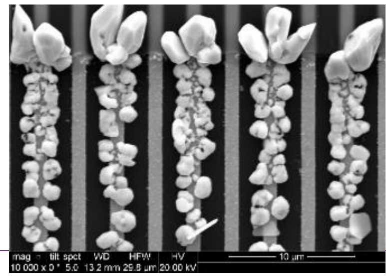
Difficult Challenges 2025-2034	*Summary of Issues*
Agri-food sensors	Gas sensors, (CO_2 NH_4, N_2O, CO, CH_4) market introduction Multiplexed water sensors (NO_3, NO_2, Do, pH, PO4, K) market introduction Multiplexed soil nutrient sensor (C, N, P, K, pH, H_20) market introduction Animal health DNA probe/target recognition, label free immunoassays, Molecular diagnostics Plan health DNA probe/target recognition, label free immunoassays, Molecular diagnostics Soil health, low cost sequencing for soil microbiome
Patient-based devices; hospital-based devices; driver impairment monitoring	Cardio meter, BP monitor, EEG monitoring for epilepsy for children, fitness monitor, energy expenditure monitor, stress monitor Vital signal monitoring, apnea and sleep monitor, pulse oximetry, congestive heart failure Drowsiness mitigation systems; driver inattention
Implantable sensors	Ear, orthopedic, neural/brain Packaging solutions, power solutions for >10 cm implantation depth available
Molecular diagnostics	Lab-on-chip DNA probe/target recognition Single particle or virus detection Biological markers analyzer m-RNA in blood

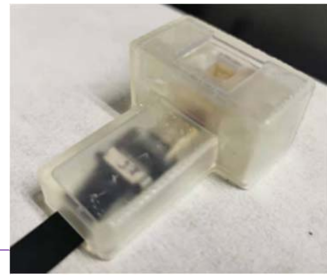
Farm to Fork – driving innovation

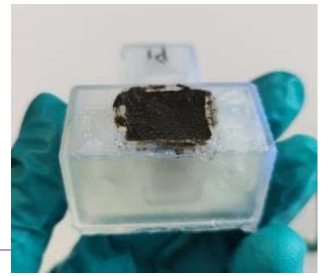
Existing approach: laboratory-based assay

- Costly and time-consuming processes
- High-cost instrument and experts required









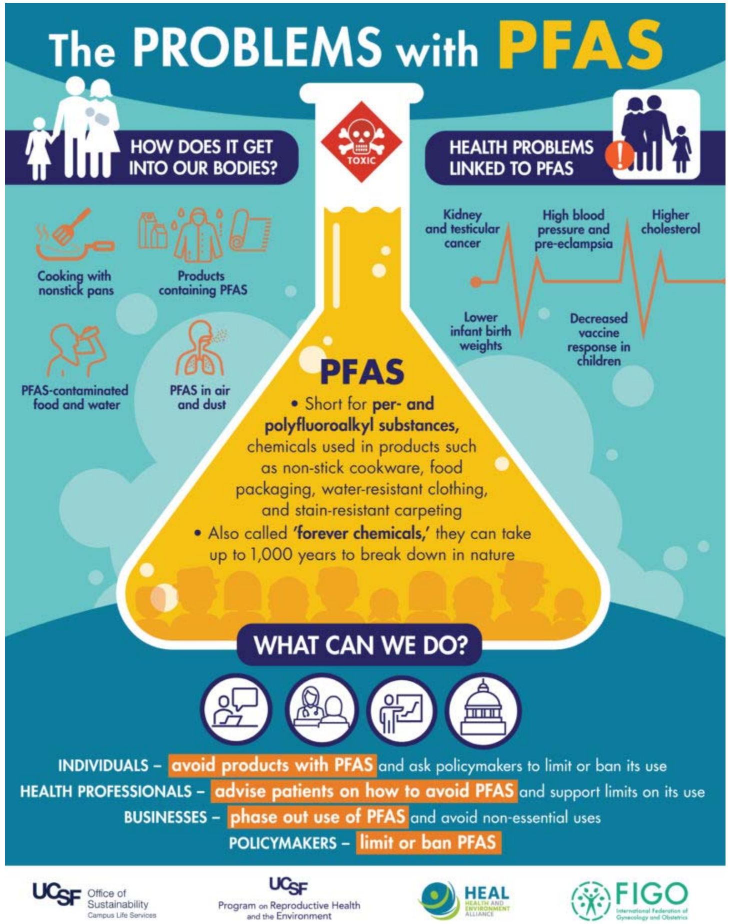
Water Framework Directive – watchlist

4th WL proposed substances

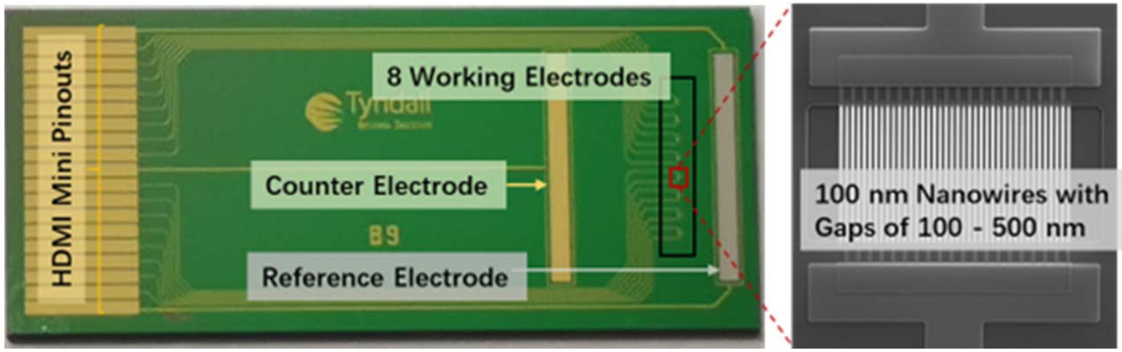
- **Industrial products**
  - Alkylphenols
  - Chloroanilines
  - Siloxanes
  - Sunscreen agents
  - UV filters
- **PPP and biocides**
  - Azoxystrobin
  - Diflufenican
  - Fipronil
  - Metazachlor
  - Pyrethroids
  - Rodenticides
- **Pharmaceuticals and illicit drugs**
  - Metformin and its transformation product (guanylurea)
  - Antibiotics
  - Illicit drugs
  - Synthetic hormones

Watchlist driving sensitivity

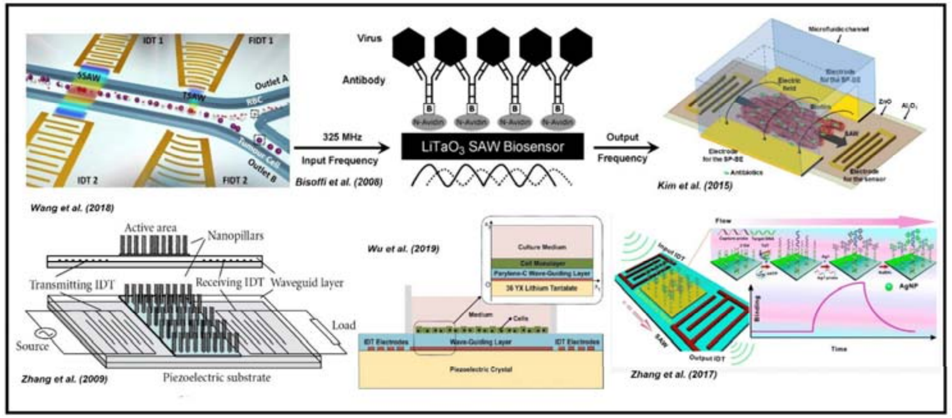
Substance/group Name	CAS Number	Use	PNEC	Matrix
Azoxystrobin	131860-33-8	Fungicide used as PPP and biocide	0.2 µg/l([1])	Water
Clindamycin	18323-44-9	Human medicine Antibiotic (lincosamides)	0.044 µg/l([2])	Water
Diflufenican	83164-33-4	Herbicide used as PPP	0.01 µg/l([1])	Water
Fipronil	120068-37-3	Insecticide	0.00077 µg/l([1])	Water



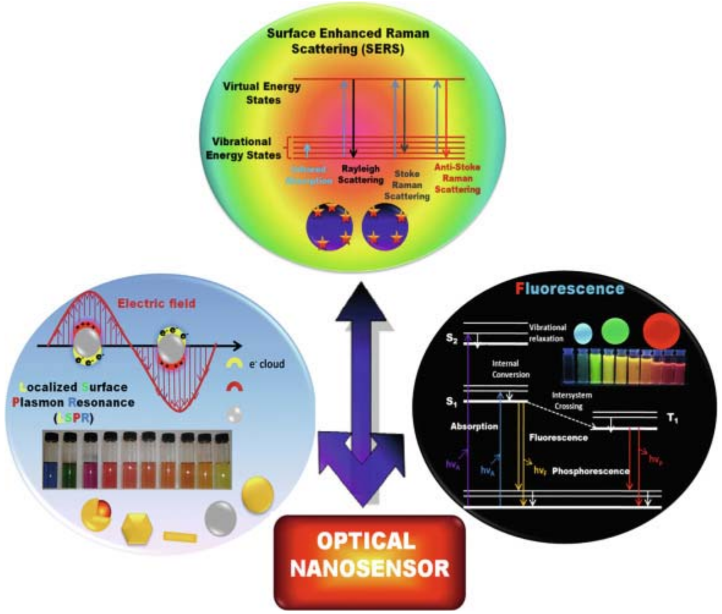
Driving new technologies…



Electrochemical Sensors



MEMs Sensors

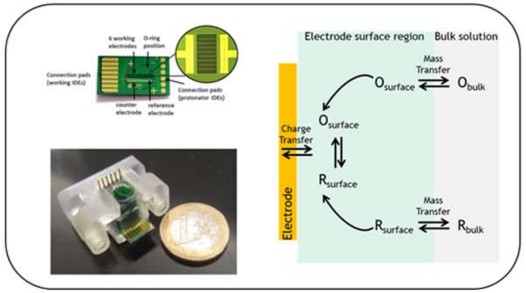


Optical Sensors

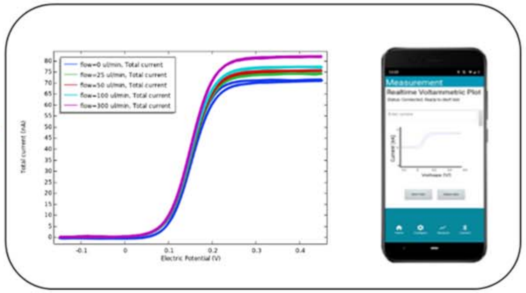
Research Challenge:

Controlling electrode – molecular interactions at the nanoscale

Chemical Interactions



Digital Output



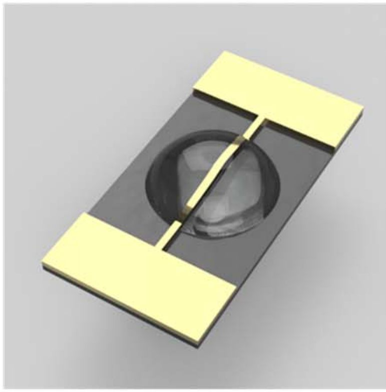
Advantages

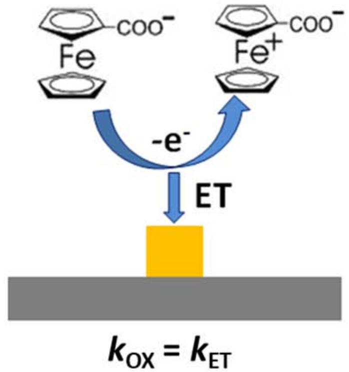
- ✓ Cost-effective
- ✓ Reasonable sensitivity
- ✓ Rapid time to results (secs to mins)
- ✓ Digital output
- ✓ Can be fabricated at high density
- ✓ Small sample volume needed

Why aren't electrochemical sensors used everywhere?

Challenges = Opportunities

- ➢ Requirement for electrolyte
- ➢ Sample preparation (e.g., pH)
- ➢ Interferant ions
- ➢ Reference electrode drift
- ➢ Lack of Specificity
- ➢ Individual Sensor Calibration

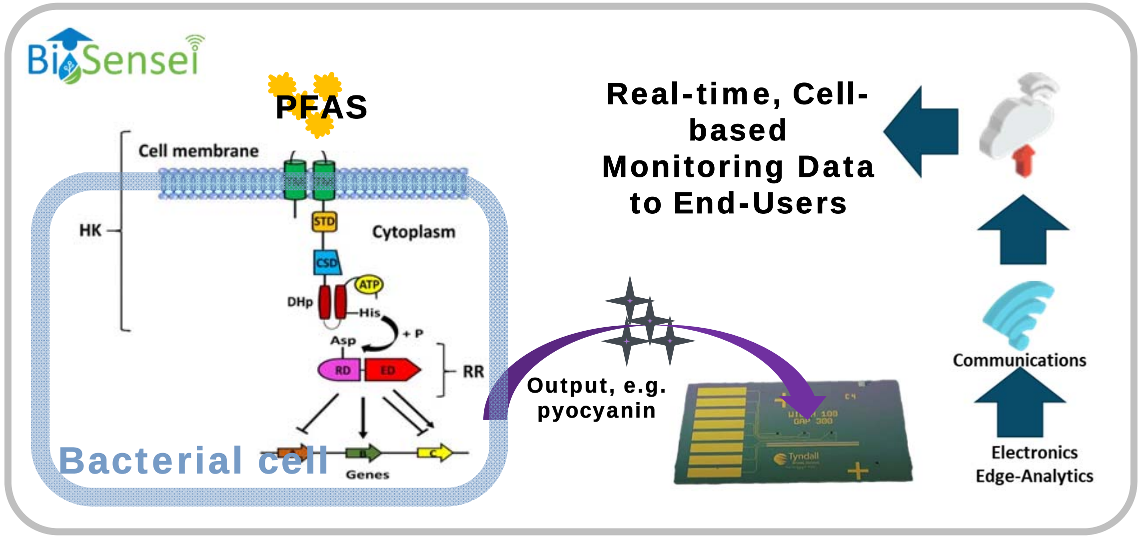




Ultimately lead to development of highly sensitive, accurate and selective sensor devices that are reliable, repeatable and reproducible.

Driving new paradigms…Cellular Sensors

- BioSensei Project ID 101135241, HORIZON-CL6-2023-ZEROPOLLUTION-01-6 Living cells as indicators of target molecules.
- Electrochemical detection of molecules emitted from cell state.
- Developing multi-modal sensing modules.
- Integration and packaging of live cells (Safe & Sustainable by Design)



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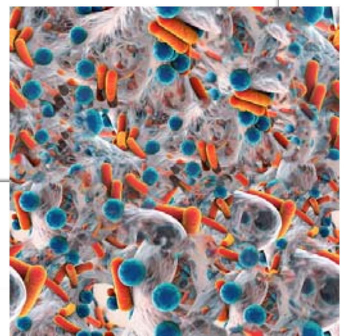

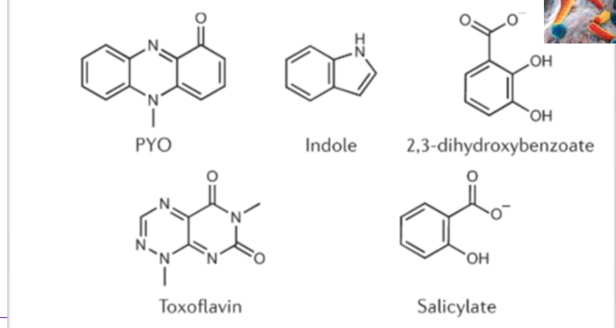

Conclusions

- Global smart sensor, market is still growing, CAGR 19.0% with the US having the major share
- As of 2024, there are approximately 18.8 billion connected IoT devices globally and is expected to reach approximately 32.1 billion by 2030
- Challenges identified for the More than Moore whitepaper 2020 still mostly relevant
- Landscape has changed increased focus on environmental sustainability
- Driving innovation in new, highly sensitive and more versatile sensors requiring more advanced sustainable (bio)materials innovation and integration